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HEAD-SLAVED TRACKING IN A SEE-THROUGH HMD: THE EFFECTS OF A SECONDARY VISUAL MONITORING TASK ON PERFORMANCE AND WORKLOAD

W. Todd Nelson, Robert S. Bolia, Chris A. Russell
Air Force Research Laboratory
Wright-Patterson AFB, Ohio

Rebecca M. Morley and Merry M. Roe
Sytronics Inc.
Dayton, Ohio

Technological advances in helmet-mounted displays (HMDs) have permitted the design of "see-through" displays in which virtual imagery may be superimposed upon real visual environments. The utility of see-through displays in multitask environments remains uncertain, especially in environments that involve switching one's attention between those tasks represented in the virtual display and those existing in the real world. The present study was designed to assess the effects of a secondary visual monitoring task on performance and workload in a head-slaved tracking task. Participants attempted to center a reticle over a moving circular target using a Kaiser Electronics SimEye 2500 HMD while concurrently performing the visual monitoring task component of the Multi-Attribute Task Battery (MATB; Comstock & Arnegard, 1992), which was displayed on a computer monitor. Task difficulty for the head-slaved tracking task was varied by manipulating time delay. Results are discussed in terms of their implications for practical implementation of see-through HMDs in multi-task environments.

INTRODUCTION

Advances in helmet-mounted display (HMD) technology have permitted the design of "see-through" displays in which virtual imagery may be superimposed upon real visual environments. Indeed, see-through HMDs have numerous potential applications ranging from augmented displays for teleoperated surgery (Durlach & Mavor, 1995) to head-slaved displays for tactical aviation (Beal & Sweetman, 1994). In the case of the latter, see-through HMDs may afford the design of head-slaved Head-Up Displays (HUDs), thereby permitting the display of flight-critical information regardless of where the pilot is looking. In addition, when see-through HMDs are used in conjunction with helmet-mounted sights and high off-boresight weapon systems, pilots are provided with the unique tactical advantage of designating targets that are up to 90° off the nose of the aircraft.

Notwithstanding their potential to enhance human perception and performance in complex task environments, see-through displays are confronted by many technological challenges, including misalignment of virtual imagery with real world objects (Azuma & Bishop, 1994), optical distortion and glare, and problems generic to most HMDs (e.g., helmet fit and discomfort, field of view limitations, suboptimal resolution, and issues involving time delay). In the case of time delay, Ricard (1994) noted the accumulation of a sizable literature demonstrating the deleterious effects of time-delayed visual feedback on an operator's ability to manually control and regulate dynamic systems. These effects also seem to be present in tasks involving head-slaved tracking. For example, Nelson and his colleagues (1998) recently showed that the addition of 67 ms of time delay significantly degraded performance efficiency in a head-slaved tracking task using a non-see-through HMD. Similar results have been reported by So and his colleagues (So, Chung, & Goonetilleke, 1999; So & Griffin, 1991).

While empirical investigations of the so-called *time delay problem* in HMDs have been abundant, these studies have typically been conducted in single-task environments, e.g., tracking tasks, in spite of the facts that 1) one of the principal advantages of see-through HMDs is their ability to support operators in multi-task environments; and 2) attentional limitations in dual-task performance are well documented (Pashler & Johnston, 1998). As an example of the former, it may prove utile for operators to track and designate targets using a see-through HMD, while concurrently monitoring control station displays in their immediate workspace. Accordingly, the purpose of the present investigation was to assess the effects of both time delay and a secondary visual monitoring task on performance efficiency and operator workload in a head-slaved visual tracking task.

METHOD

Participants

Seven naïve participants, 4 females and 3 males, served in the experiment. Their ages ranged from 20 to 32 years with a mean of 24.35 years. Participants reported normal or corrected-to-normal vision, and indicated that they were not

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highly susceptible to motion sickness. In addition, all participants reported no prior experience with head-slaved tracking tasks using an HMD. Participants were paid for their participation.

Experimental Design

A within-subjects design was employed in which two time delay conditions (*nominal* and *nominal + 100 ms*) were combined with two task conditions (*single* and *dual*) and five experimental sessions. The single task condition required only the performance of the head-slaved tracking task, while the dual task required participants to perform the tracking task and the monitoring task concurrently. The order of the time delay condition was randomized across participants, while the order of the task conditions was fixed within each session (i.e., blocks of single-task trials preceded the dual-task trials).

Apparatus and Procedure

Each experimental session included 20 5-min head-slaved tracking trials. The first 10 trials served as a baseline condition for head-slaved tracking performance and did not require the participant to perform the visual monitoring task. Trials 11-20 involved both the tracking and monitoring tasks. Prior to the initiation of the main experimental sessions, all participants completed five 5-min practice trials of the secondary visual monitoring task. The purpose of the practice trials was to acquaint participants with the response procedures for the task and to ensure that they were able to perform the task at ceiling level.

Participants used a Kaiser Electronics SimEye 2500 HMD to track a moving visual target. The SimEye 2500 HMD employs an optical relay system to transfer video images from a pair of green phosphor monochrome cathode ray tubes (CRTs) to the participant's eyes. It features a high resolution (1280 × 1024 pixels) binocular display and was configured to provide subjects with a 60° (horizontal) × 40° (vertical) field of view (FOV). The optical focus range of the SimEye 2500 extends from 3.5 feet to infinity, and was set to infinity in the present experiment. The SimEye 2500 weighs approximately four pounds and was configured as a see-through display, thereby allowing participants to view the visual display on which the monitoring task was presented.

The head-slaved tracking task employed target motion patterns, or forcing functions, that consisted of the sum of three sine waves with fundamental frequencies of 0.067, 0.117, and 0.233 Hz in azimuth, and 0.083, 0.167, and 0.217 Hz in elevation. Target motions were restricted to ±30° in azimuth, and ±20° in elevation. Different target motions were generated for each trial by randomly assigning phase values at each of the three fundamental frequencies in azimuth and elevation.

Head position and orientation were measured by an Ascension Bird tracker. The Bird consists of a DC magnetic-field transmitter and a receiver that was mounted atop the HMD. The Bird provides six degrees-of-freedom tracking at 120 Hz while minimizing interference caused by nearby metallic objects. All phases of the head-slaved tracking task and data collection were governed by a 200 MHz personal computer. Target and head position data were collected at 60 Hz for each 5-min trial.

The nominal time delay in the head-slaved tracking system was determined to be 46 ms. The imposed time delay consisted of six frames of delay, or 100 ms (six frames @ 16.7 ms). Thus, in the time delayed condition, the total time delay of the system was approximately 146 ms.

The secondary monitoring task consisted of the systems monitoring task from the Multi-Attribute Task Battery (MATB; Comstock & Arnegard, 1992). In short, the task comprised a set of four gauges with moving pointers. Under non-signal conditions, the moving pointers oscillated around the center tickmark by no more than one mark from the center tickmark on each of the gauges. A critical signal consisted of any of the four pointers moving more than one mark from the center of the gauge in either direction. Participants were instructed to inspect the gauges for critical signals and to make the appropriate keyboard response as soon as one was detected. Critical signals not detected within 10 s were scored as missed signals; conversely, responses to non-signals were scored as errors of commission. The MATB monitoring task also included a pair of system status displays positioned above the four gauges. The normal or non-signal condition for these displays were the presence of a green light on the left display and a black fill on the right display. Critical signals consisted of the left display shifting from green to black, or the right display shifting from black to red. Again, participants were instructed to inspect the system status display for critical signals and to respond as soon they detected a change in system status. During each of the 5-min experimental trials 12 critical signals were presented – two critical signals for each of the four gauges and two critical signals for each of the system status displays.

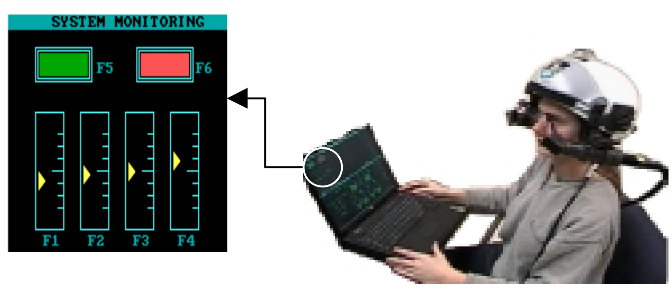


Figure 1. Participant performing head-slaved tracking task and secondary visual monitoring task.

Upon arrival, participants were presented with an overview of the experimental procedure, received instructions, and donned the HMD. Proper fit and viewing quality in the HMD were achieved by making adjustments to its inter-pupillary distance controls, vertical, tilt, and axial helmet angles, chin strap, variable-thickness foam pads, and inflatable air-bladder. Participants completed 20 5-min head-slaved tracking trials per experimental session – ten trials with and without the additional visual monitoring task (see Figure 1). Each 5-min trial was preceded by a 5 s target acquisition period to ensure that participants had acquired the target at the onset of the trial.

Tracking performance, however, was based on the 5-min trial and did not include the 5 s acquisition period. Participants completed the NASA Task Load Index at the completion of 5-min trial and received a 10-min rest period after the completion of five experimental trials.

RESULTS

Head-slaved Tracking Performance

For each 5-min head-slaved tracking trial, target and head position data were used to calculate two indices of error in the time domain: percent time on target (TOT) and root mean squared (RMS) error. The latter provides an unsigned measure of error between the center of the aiming reticle and the center of the visual target; the former provides a measure of the percentage of time that the center of the aiming reticle is within the boundary of the visual target.

Time on Target. Mean TOT percentages for all experimental conditions were subjected to a 2 (time delay) × 2 (task) × 5 (trials) repeated measures analysis of variance, which revealed main effects of *time delay*, $F(1,6) = 9.04$, $p < .05$, and *task*, $F(1,6) = 46.37$, $p < .05$, and a significant *time delay × task* interaction, $F(1,6) = 6.66$, $p < .05$. All other sources of variance lacked statistical significance (i.e., $p > .05$). The *time delay × task* interaction is depicted in Figure 2, which shows the decrements in tracking performance associated with the addition of both time delay and the visual monitoring task. The interaction can be explained by noting that the presence of the additional time delay degraded tracking efficiency to a greater extent in the tracking-only condition than it did when participants were required to perform the monitoring task.

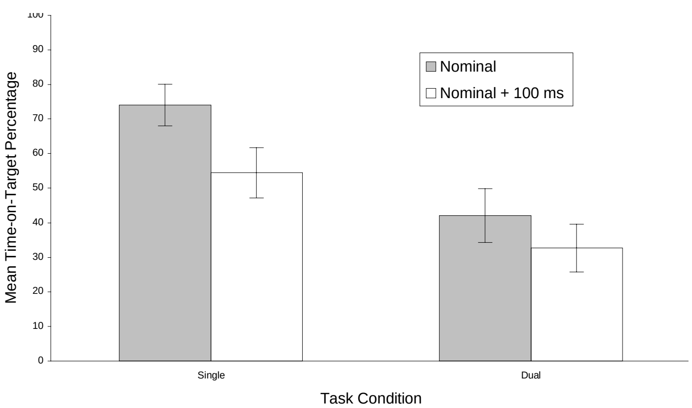
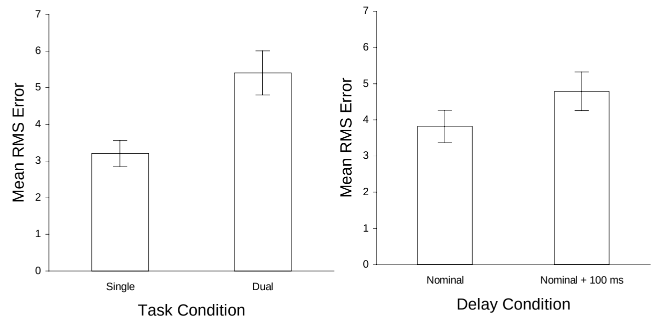


Figure 2. Mean percent time-on-target associated with the two time delay conditions under each level of the task condition.

Root Mean Squared Error. Mean RMS Errors were submitted to a similar repeated measures ANOVA, revealing significant main effects of *time delay*, $F(1,6) = 7.12$, $p < .05$ and *task*, $F(1,6) = 36.39$, $p < .05$, but failing to disclose the significant *time delay × task* interaction revealed by the analysis involving the TOT data. The main effects are illustrated in Figures 3a and 3b.



Figures 3a and 3b. Mean RMS error for each task condition (a) and for each level of time delay (b).

Visual Monitoring Performance

Performance on the secondary visual monitoring task was determined for each experimental session and scored in terms of correct detections (hits) and errors of commission (false alarms).

Correct Detections. Mean percentages of correct detections for the two *time delay* conditions across the five experimental trials are presented in Table 1. Inspection of the table reveals that performance on the secondary monitoring task approached ceiling performance and that performance was rather consistent across the experimental conditions. A 2 (time delay) × 5 (trials) repeated measures ANOVA of these data confirmed these impressions by revealing no significant main effects or interactions.

Table 1
Mean Percent Correct Detections

	Experimental Trials					
Time Delay Condition	1	2	3	4	5	$\overline{X}$
Nominal	97.6	98.8	97.6	97.6	99.9	98.3
Nominal + 100 ms	97.6	95.2	96.4	98.8	97.6	97.1

Errors of Commission. Mean percentages of errors of commission, or false alarms, are shown in Table 2 for all experimental conditions. Review of these data indicates that the occurrence of false alarms varied across experimental conditions; however, an ANOVA of these data failed to reveal any systematic sources of variance.

Table 2
Mean Percent Errors of Commission

	Experimental Trials					
Time Delay Condition	1	2	3	4	5	$\overline{X}$
Nominal	4.8	20.2	8.3	10.7	7.1	10.2
Nominal + 100 ms	8.3	15.5	9.5	9.5	4.8	9.5

Operator Workload Ratings

The NASA Task-Load Index (NASA-TLX; Hart & Staveland, 1988), a multidimensional scale of perceived mental workload, was used to provide subjective estimates of the information processing demands associated with the experi-

mental task. The NASA-TLX provides a global measure of overall workload (on a scale of 0 to 100), and also identifies the relative contributions of six sources of workload: (1) Mental Demand, (2) Physical Demand, (3) Temporal Demand, (4) Performance, (5) Effort, and (6) Frustration.

Overall Workload Ratings. Mean overall workload ratings were submitted to a 2 (time delay) × 2 (task) × 5 (trials) repeated measures ANOVA, revealing a significant main effect of *task*, $F(1,6) = 10.42$, $p < .05$, but neither significant main effects of *time delay* nor *trial* nor significant interactions involving any of the factors. Mean overall workload scores for the tracking and tracking+monitoring task conditions were 38.75 and 46.74, respectively.

Subscale Ratings. Mean weighted ratings for the NASA-TLX subscales were submitted to a 5 (subscale) × 2 (time delay) × 2 (task) × 5 (trials) repeated measures ANOVA. Weighted ratings for the *Frustration* subscale contributed least to ratings of workload and were subsequently excluded from the ANOVA in order to meet the independence assumption of the analysis. Significant sources of variance resulting from the analysis included a main effect of *task*, $F(1,6) = 8.39$, $p < .05$ and a significant *task* × *subscale* interaction, $F(4,24) = 2.87$, $p < .05$. All other sources of variance were not significant; however, it is worth noting that the effects of *subscale* and *time delay* were associated with *p*-values of .055 and .053, respectively. The *task* × *subscale* interaction is shown in Figure 4, in which mean weighted subscale ratings are plotted for the tracking and tracking+monitoring task conditions across the six subscale dimensions. Post hoc pairwise comparisons (Bonferroni-adjusted *t*-tests) of the task conditions at each subscale revealed that the addition of a secondary monitoring task resulted in significantly greater ratings of *Mental Demand*, but failed to show differences for the other subscales.

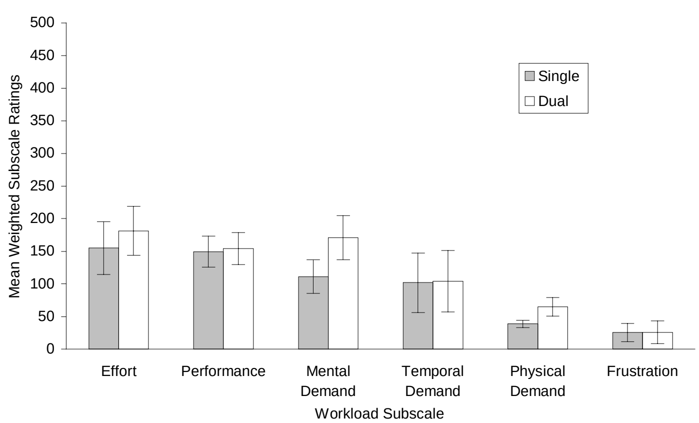


Figure 4. Mean weighted subscale ratings (NASA-TLX) under each level of the task condition.

CONCLUSION

The present study represents an initial effort to evaluate the effects of a secondary monitoring task on head-slaved tracking performance and workload using a see-through HMD. Additionally, the effects of *time delay* on head-slaved tracking were investigated in the context of a dual-task environment, thereby extending the work in this area (see Nelson et al., 1998; So & Griffin, 1991). While this experiment was conducted in a reasonably controlled laboratory setting, the findings reported herein are anticipated to generalize to more applied situations which incorporate see-through HMDs in dual-task environments.

Hitherto, time delay in HMD systems has been regarded as one of the principal constraints on their functional utility, especially in tightly-coupled control tasks. Yet the data presented here compel one to conclude that its effects – on workload as well as performance – may be rendered inconsequential by the introduction of a secondary task of even modest complexity. Such an outcome may be of import to human factors professionals who prematurely recommend the adoption of see-though HMDs as a solution to problems inherent in multi-task work domains.

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